Temporal and Spatial Variations in Freshwater 14C Reservoir Effects: Lake Mývatn, Northern Iceland

TEMPORAL AND SPATIAL VARIATIONS IN FRESHWATER ^{14}C RESERVOIR EFFECTS: LAKE MÝVATN, NORTHERN ICELAND

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ABSTRACT. Lake Mývatn is an interior highland lake in northern Iceland that forms a unique ecosystem of international scientific importance and is surrounded by a landscape rich in archaeological and paleoenvironmental sites. A significant freshwater reservoir effect (FRE) has been identified in carbon from the lake at some Viking (about AD 870–1000) archaeological sites in the wider region (Mývatnssveit). Previous accelerator mass spectrometry (AMS) measurements indicated this FRE was about 1500–1900 ^{14}C yr. Here, we present the results of a study using stable isotope and ^{14}C measurements to quantify the Mývatn FRE for both the Viking and modern periods. This work has identified a temporally variable FRE that is greatly in excess of previous assessments. New, paired samples of contemporaneous bone from terrestrial herbivores and omnivores (including humans) from Viking sites demonstrate at least some omnivore diets incorporated sufficient freshwater resources to result in a herbivore-omnivore age offset of up to 400 ^{14}C yr. Modern samples of benthic detritus, aquatic plants, zooplankton, invertebrates, and freshwater fish indicate an FRE in excess of 5000 ^{14}C yr in some species. Likely geothermal mechanisms for this large FRE are discussed, along with implications for both chronological reconstruction and integrated investigation of stable and radioactive isotopes.

INTRODUCTION

Radiocarbon measurements can provide absolute age assessment of samples from terrestrial, marine, and freshwater carbon (C) reservoirs (e.g. Nydal 2000; Trumbore 2000; Bird 2006). The average reservoir ^{14}C activity is a function of atmosphere-reservoir CO_2 exchange rates, internal reservoir mixing dynamics, and the quantity and ^{14}C activity of carbon inputs (Geyh and Schleicher 1990; Levin and Hesshaimer 2000). As the mean atmospheric ^{14}C residence time is of the order of 5 yr (Levin and Hesshaimer 2000), the ^{14}C activity of photosynthetic primary producers and herbivorous primary consumers in the terrestrial biosphere is assumed to be equivalent to the contemporaneous atmosphere. However, the ^{14}C activity of other C reservoirs may be offset from the atmosphere/biosphere and this offset (R) is known as a reservoir effect (Stuiver et al. 1986; Stuiver and Braziunas 1993). The conventional ^{14}C age of samples affected by a reservoir effect is older than the ^{14}C age of contemporaneous samples formed in the terrestrial/atmospheric C reservoir. ^{14}C reservoir effects not only affect samples formed in the reservoir but also organisms that obtain dietary carbon from within the reservoir. If unrecognized and unquantified, ^{14}C reservoir effects can severely limit the accuracy of chronological models based upon both these sample types.

The primary ^{14}C sources in freshwater (aquatic) environments are atmospheric CO_2 exchange at the air-water interface and groundwater input of dissolved inorganic carbon (DIC) (Geyh et al. 1998). Input of low ^{14}C-activity carbon, or restriction of atmosphere-water CO_2 exchange (e.g. via density stratification or ice cover), results in a freshwater ^{14}C reservoir effect (FRE). FRE values can be extreme; examples of up to 18,000 yr in the Dry Valleys of Antarctica are attributed to input of

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ancient glacial meltwater (Hall and Henderson 2001). FREs are also a common feature in areas of carbonate geology, due to dissolution of ^{14}C-"dead" $CaCO_3$ (e.g. Lanting and van der Plicht 1998), and are well-documented in bone collagen from prehistoric human communities that fed on an aquatic resource base (Cook et al. 2001; Culleton 2006; Fischer et al. 2007).

We have previously demonstrated the existence of a large FRE in carbon from Lake Mývatn during the period cal AD 868–968 (Ascough et al. 2007). This FRE was estimated at 1500–1900 ^{14}C yr, based upon analysis of paired samples of Arctic char and cattle bone collagen at the site of Hrísheimar. The region contains an extraordinary wealth of archaeological and paleoenvironmental sites (McGovern et al. 2006, 2007; Lawson et al. 2007), a significant number of which were established very early during the initial human colonization of Iceland, with archaeological material in direct stratigraphic contact with the AD 871 ± 2 landnám tephra layer (Grönvold et al. 1995). The extensive early settlement of Mývatnssveit appears linked to the high biological productivity of the region, with Lake Mývatn playing a key role. Today, this large (37 km^2) lake in the interior highlands is a site of international scientific interest and is designated a conservation area, in light of the wealth and diversity of the lake ecology (Einarsson 2004). During the Viking period, the Mývatn ecosystem appears to have been equally rich and the inhabitants of the region exploited a wide resource base including a large proportion of aquatic dietary resources such as freshwater fish, waterfowl and their eggs (McGovern et al. 2006, 2007).

Aquatic resource use by Viking peoples in Mývatnssveit means the FRE has important implications for the accuracy of archaeological chronologies. Indeed, the ^{14}C ages of some individuals from Viking-period graves appear anomalously old (McGovern et al. 2007) and a 1100 ^{14}C yr offset between contemporaneous pig and cattle bone at the site of Hofstaðir is attributed to the FRE (Ascough et al. 2007). However, the impact of the Mývatn FRE upon archaeological samples has not yet been subject to a systematic investigation. Here, we present results from such a study, examining the evidence for FRE effects in a suite of archaeological material containing omnivorous organisms (pigs and humans) likely to have consumed aquatic resources (e.g. freshwater fish). To identify if bone ^{14}C ages were affected by the FRE, we compared the ^{14}C ages of the pig and human bone collagen with the terrestrial biospheric ^{14}C ages of contemporaneous herbivorous mammal bones from Viking-period midden deposits. We also conducted further interpretation on previously published data from paired samples of human bone and terrestrial mammals from graves within Mývatnssveit (see McGovern et al. 2007).

The FRE offset in an individual ^{14}C age is proportional to the quantity of aquatic carbon consumed, which is likely to vary between individuals. To attribute an observed ^{14}C offset to the FRE, it is useful to assess whether a sample contains aquatic-derived carbon. Stable isotope measurements of carbon (δ^{13}C) and nitrogen (δ^{15}N) have been used successfully to identify aquatic versus terrestrial resource use in prehistoric communities (e.g. Schoeninger et al. 1983; Arneborg et al. 1999; Cook et al. 2001; Richards et al. 2001). The stable isotope signatures of ecosystems differ due to physical and biochemical fractionation effects. If differences between 2 ecosystems are sufficiently large, it is possible to discriminate between individuals sourcing carbon from different pools via stable isotope measurements on bone collagen. This is because δ^{13}C and δ^{15}N values in mammalian bone collagen reflect the values of the dietary resources (Ambrose and Norr 1993; Jim et al. 2004). Icelandic terrestrial vegetation uses the Calvin-Benson (C_3) photosynthetic pathway, where C_3 plants have a typical δ^{13}C of –20‰ to –30‰ (Ehrlinger et al. 1997, 2002). The δ^{13}C values of archaeological cattle bones from Mývatnssveit range from –20.9‰ to –21.7‰ (Ascough et al. 2007), typical of terrestrial mammals in C_3-dominated environments, given a trophic level fractionation of 0–2‰ (e.g. DeNiro and Epstein 1978; Post 2002). However, δ^{13}C values of –15.0 to –15.2‰ in freshwater fish

from Lake Mývatn suggest that the aquatic carbon $\delta^{13}C$ signature is significantly heavier than the terrestrial signature in Mývatnssveit (Ascough et al. 2007). Because enrichment in $\delta^{15}N$ of 1.3–5.3‰ occurs with successive trophic levels (Minagawa and Wada 1984; Cabana and Rasmussen 1994, 1996), the complexity of aquatic foodwebs relative to terrestrial systems means that the $\delta^{15}N$ values of organisms feeding in an aquatic system may be significantly heavier than those in a terrestrial system (Schoeninger and DeNiro 1984). Therefore, samples from Mývatnssveit containing an aquatic carbon component would be expected to show heavier $\delta^{13}C$ and $\delta^{15}N$ values than organisms consuming a terrestrial diet.

It is possible to correct sample ^{14}C ages for a reservoir effect (*R*) if 1) the proportion of non-terrestrial carbon within a sample can be established (e.g. via stable isotope analysis), and 2) *R* can be accurately quantified for the particular time period under study. Quantification is greatly complicated if there are significant temporal and spatial variations in *R*. FRE values in other freshwater systems show significant variability on both scales, as the proportion and ^{14}C activity of carbon inputs to the system fluctuate (e.g. Geyh et al. 1998). In Mývatn, the range in FRE values calculated from Arctic char bones in a single, constrained archaeological deposit was 1500–1900 ^{14}C yr (Ascough et al. 2007) and suggests that spatial variation of at least 400 ^{14}C yr was in operation at cal AD 868–968. To investigate the potential for FRE variation, we examined the ^{14}C activity within modern samples from the lake and surrounding environment, comparing calculated FRE values for the Viking and modern periods. Additionally, samples were taken from a variety of trophic levels within the lake to test FRE variation between different components of the aquatic ecosystem and also to establish whether there was any covariance between stable isotope ($\delta^{13}C$ and $\delta^{15}N$) and ^{14}C measurements.

Understanding the potential for FRE variation also requires an understanding of the potential mechanisms for variation. The work of Sveinbjörnsdóttir et al. (1992, 1995) has demonstrated that Icelandic groundwater often exhibits old apparent ^{14}C ages of up to ~20,000 ^{14}C yr as a result of geothermal activity. The ^{14}C concentration of water samples from Mývatn were therefore measured as part of this work to test the hypothesis that the FRE results from the introduction of low ^{14}C-activity carbon via groundwater springs at the eastern edge of Lake Mývatn (Figure 2). If correct, variations in the FRE could therefore arise via fluctuations in levels of geothermal activity in active zones close to the lake.

METHODOLOGY

Sample Material

We obtained samples of archaeological material from 2 sites in Mývatnssveit; Hofstaðir (65°61′N, 17°16′W) and Hrísheimar (65°52′N, 17°10′W) (see Figure 1). At both sites, we retrieved the samples from stratigraphically secure and spatially delimited midden contexts, where there is a high probability that material within the deposit represents a short period of discard. We obtained pairs of cow (*Bos* sp.) and pig (*Sus* sp.) bone from 3 contexts at Hofstaðir and 2 contexts at Hrísheimar. In addition, we obtained samples of bone from Arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta*) located in a single context at Hofstaðir. These were from 2 articulated fish of each species and were analyzed in order to verify that the apparent age range of fish from Viking deposits was commensurate with the previous assessment of 1500–1900 ^{14}C yr (Ascough et al. 2007). Although no direct paired terrestrial samples were measured for these samples, the earliest midden deposits at this site are located immediately above a tephra ash layer from the Veiðivötn system, dated to about AD 940 (Sigurgeirsson et al. 2002; McGovern et al. 2006).

We also compared previously published ^{14}C measurements of terrestrial mammal and human bone collagen from 3 Viking-period graves at the sites of Grímsstaðir, Gautlönd, and Ytri-Neslönd (Figure 1) in Mývatnssveit. At least 1 terrestrial mammal and human had been interred simultaneously in each grave (McGovern et al. 2007). In 3 instances, the terrestrial mammal was horse and in 1 case the mammal was dog. $\delta^{13}C$ and $\delta^{15}N$ measurements of this material are also available (McGovern et al. 2007). In addition, new ^{14}C and stable isotope measurements were performed on a further pairing of human and terrestrial mammal bone from a grave at the site of Glaumbær, in the lowland valley of Reykjaldalur, ~30 km north of Mývatn (Figure 1). Both previous and new data were generated as part of the "Landscapes circum-Landnám" project (Edwards et al. 2004).

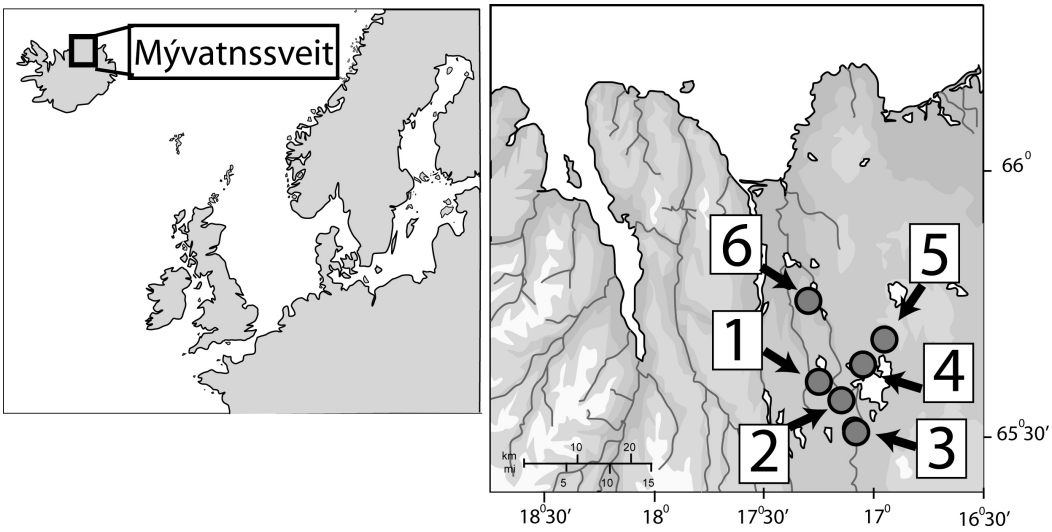

Figure 1 Map of Mývatnssveit (after Ascough et al. 2007), showing the location of archaeological sites from which material was analyzed for this research: 1- Hofstaðir; 2- Gautlönd; 3- Hrísheimar; 4- Ytri-Neslönd; 5- Grímsstaðir; 6- Glaumbær.

We obtained 17 samples of modern biota, detritus, and water from in and around Lake Mývatn in July 2007 and 2008 (see Figure 2; Table 2). We collected individual freshwater fish, including Arctic char (*Salvelinus alpinus*) and three-spined stickleback (*Gasterosteus aculeatus*) by gill net and trapping. We also collected larvae of the chironomid *Tanytarsus gracilentus*, and lake benthic detritus by drop-core while bulk zooplankton were collected by plankton net at Station 33, a sampling station situated approximately in the center of the Mývatn South Basin (Einarsson and Örnólfsdóttir 2004). We hand-collected aquatic plants (*Myriophyllum alterniflorum* and *Potamogeton perfoliatus*) from a boat in the Mývatn North Basin. Adult specimens of *Tanytarsus gracilentus* were collected by sweep net at the lakeside. Á Einarsson provided cow bone from an animal farmed in proximity to Lake Mývatn. Samples of grass (*Poa* sp.) were taken ~10 m from the lake shore at 2 locations: Kalfaströnd and Haganes. While the $\delta^{13}C$ of Icelandic terrestrial herbs and grasses appears to vary by <6‰, the $\delta^{15}N$ of these plants shows a much wider range of between –9.3‰ to +5.6‰ (Wang and Wooler 2006). We therefore took samples of grass and field horsetail (*Equisetum arvense*) from Seljahjallagil, a location ~5 km from Lake Mývatn for comparative $\delta^{13}C$ and $\delta^{15}N$ measurement. We obtained samples of feathers from individual birds of 3 species—horned grebe (*Podiceps auritus*), mallard duck (*Anas platyrhynchos*), and common snipe (*Gallinago gallinago*)—that had been recently killed on the lakeside. All samples were air-dried at 30 °C then freeze-dried and stored in cleaned glass vials or plastic bags prior to analysis.

We collected water samples from 3 sites (Figure 2). Station 33 is located approximately in the center of the South Basin, and surface lake water was obtained at <0.5 m depth. We also collected water from the point of ingress of hot geothermal springs at Helgavogur and of cold groundwater springs at Grjotavogur (see Figure 2). We collected the water by hand into opaque 500-mL flasks. The flasks were refilled 3 times and overfilling with the water to ensure that no headspace existed in the flask. We refrigerated these samples at <5 °C within 1 hr of collection.

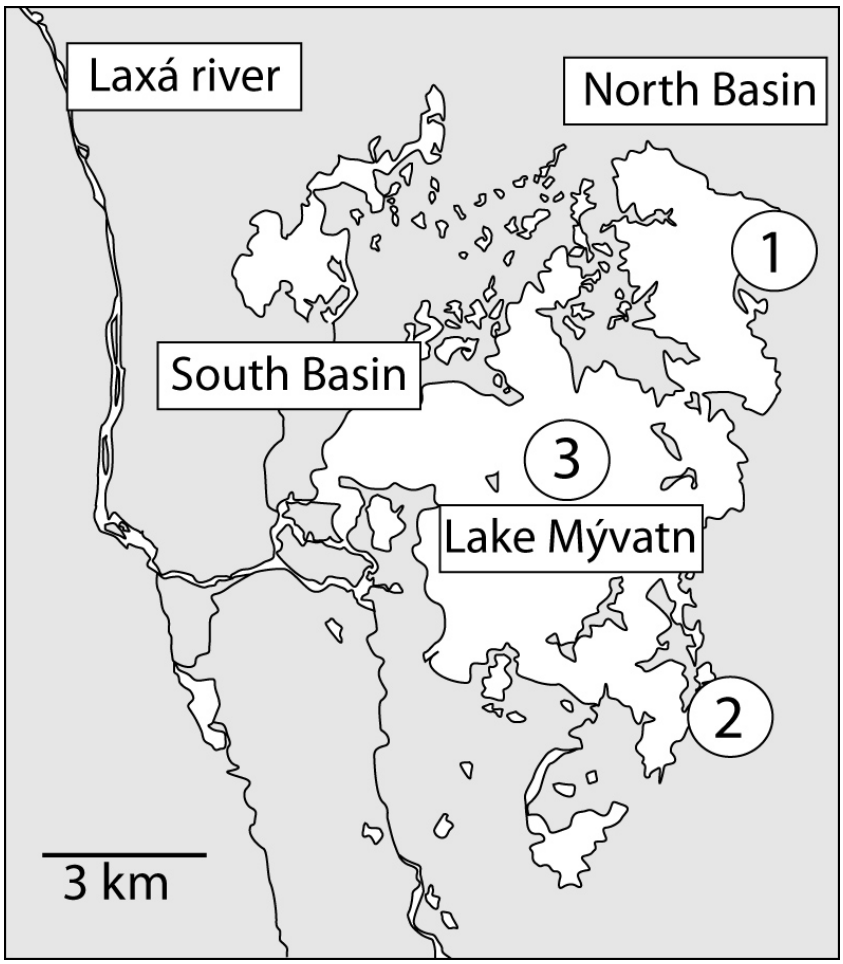

Figure 2 Map of Lake Mývatn (after Einarsson and Örnólfsdóttir 2004), showing the sampling locations for modern material and water samples: 1- Helgavogur; 2- Grjotavogur; 3- Station 33.

Pretreatment

Pretreatment of bone for ^{14}C and stable isotope measurements of archaeological and modern samples followed a modification of Longin (1971) for collagen extraction. For samples of modern freshwater fish, dried flesh was separated from bone using a scalpel. Individual samples of aquatic and terrestrial plants, detritus, *Tanytarsus gracilentus*, and bulk zooplankton were homogenized by grinding using an agate mortar and pestle. Feathers were thoroughly washed in deionized water and

air-dried. CO_2 was then obtained from the solid samples by combustion in sealed quartz tubes according to the method of Vandeputte et al. (1996).

We obtained CO_2 from DIC in water samples by hydrolysis with 85% orthophosphoric acid under vacuum in a precleaned flask. We bubbled helium gas through the sample following addition of acid in order to displace any dissolved CO_2 in the sample/acid mixture. We produced process standards of Iceland dopplespar calcite and IAEA-C2 by acid hydrolysis in water previously purged of CO_2.

Following combustion or hydrolysis, we took an aliquot of sample CO_2 for off-line $\delta^{13}C$ determination on a VG SIRA 10 isotope ratio mass spectrometer. We employed NBS 22 (oil) and NBS 19 (marble) as standards. For water samples, we determined $\delta^{13}C$ and $\delta^{18}O$ values off-line on a VG OPTIMA isotope ratio mass spectrometer. We also converted a 3-mL subsample of the extracted CO_2 to graphite for AMS measurement using the method of Slota et al. (1987). We measured sample $^{14}C/^{13}C$ ratios at 245 keV on the SUERC SSAMS with carbon in the +1 charge state. We calculated calibrated age ranges for terrestrial archaeological material using OxCal 3.10 (Bronk Ramsey 1995, 2001) with the IntCal04 atmospheric calibration curve data set (Reimer et al. 2004).

We made $\delta^{13}C$ and $\delta^{15}N$ measurements by continuous-flow isotope ratio mass spectrometry (CF-IRMS) using a Costech elemental analyzer coupled via a ConFlo III to a Thermo Finnegan Delta^{plus} XL. We undertook duplicate measurements for each sample, where a sample run included a mix of samples, laboratory standards, and blanks. Precision on internal standards was better than ±0.2‰ (1 σ) for $\delta^{13}C$ and ±0.3‰ (1 σ) for $\delta^{15}N$. Isotope values are reported as per mil (‰) deviations from the VPDB and AIR international standards for $\delta^{13}C$ and $\delta^{15}N$, respectively.

RESULTS

Archaeological Samples

On the basis of the ^{14}C ages of the terrestrial (cow) samples that are paired with the pig bone samples (Table 1) and in the absence of any FRE, the pig bones should return dates in the same age interval, i.e. 1030–1160 ^{14}C yr BP (AD 896–1148 AD at 2 σ). Similarly, on the basis of the ages of the horse bones that are paired with the human bone samples (Table 1), the latter should cover approximately the same range of 1105–1200 ^{14}C yr BP (870–1019 cal yr AD at 2 σ). For 4 sets of paired archaeological cow and pig bone collagen, the ^{14}C ages of both species are within error (Table 1). $\delta^{13}C$ values are between –20.3‰ and –21.4‰ for cow bone from all deposits, and the majority of pig bone $\delta^{13}C$ values are very similar (between –20.1‰ and –21.5‰) and typical for a diet of C_3 terrestrial vegetation. However, 1 pig bone age (SUERC-3438) is 400 ^{14}C yr older than the paired cow bone sample (SUERC-3433). The $\delta^{13}C$ for the pig in this instance is slightly heavier, at –19.8‰. $\delta^{15}N$ values for all samples are between +1.0‰ and +5.9‰ for cow bone and between +0.1‰ and +4.6‰ for pig bone, with some evidence for a relationship between isotopic value and ^{14}C offset. Inclusion of the previous pig bone $\delta^{13}C$ and ^{14}C offset from Ascough et al. (2007) in this data set strengthens the relationship between these variables significantly (Figure 3A and 3B).

In paired samples of horse or dog and human bone from Viking graves where duplicate analyses from a single individual were undertaken, the ^{14}C ages of all duplicates are within error. At Glaumbær, the ^{14}C ages of the horse and human bone collagen samples are within error. At Grímsstaðir, the human bone sample (SUERC-2018) is 100 ^{14}C yr older than that of the horse bone sample from the same grave. At Ytri-Neslönd, the human bone analyses (SUERC-2016 and -2660) indicate an offset of ~200 ^{14}C yr over the 2 horse bone analyses. Finally, at Gautlönd the ages for dog and human bones are within error.

Table 1 Comparison of ^{14}C ages and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values for paired archaeological samples from sites in Mývatnssveit, and the site of Glaumbær in the lowland valley of Reykjaldalur. Measurements marked * are reported in McGovern et al. (2007).

	Terrestrial samples					Aquatic/mixed samples				
Site	Sample type	Sample ID	^{14}C age BP (±1 σ)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Sample type	Sample ID	^{14}C age BP (±1 σ)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Hofstaðir	Cow (*Bos* sp.)	SUERC-3431	1045 ± 35	–20.3	1.6	Pig (*Sus* sp.)	SUERC-3432	1040 ± 40	–21.5	0.5
Hofstaðir	Cow (*Bos* sp.)	SUERC-3429	1160 ± 35	–21.0	5.9	Pig (*Sus* sp.)	SUERC-3430	1170 ± 40	–21.0	4.6
Hofstaðir	Cow (*Bos* sp.)	SUERC-3433	1030 ± 35	–20.9	3.8	Pig (*Sus* sp.)	SUERC-3438	1430 ± 35	–19.8	3.7
Hrísheimar	Cow (*Bos* sp.)	SUERC-3446	1080 ± 35	–21.4	1.0	Pig (*Sus* sp.)	SUERC-3442	1120 ± 35	–20.1	1.3
Hrísheimar	Cow (*Bos* sp.)	SUERC-3439	1085 ± 35	–20.9	2.3	Pig (*Sus* sp.)	SUERC-3440	1150 ± 40	–21.3	0.1
Hofstaðir	–	–	–	–	–	Arctic char (*S. alpinus*)	SUERC-11539	4930 ± 35	–12.5	5.7
Hofstaðir	–	–	–	–	–	Brown trout (*Salmo trutta*)	SUERC-11540	4675 ± 35	–12.2	6.8
Glaumbær	Horse	SUERC-2029	1185 ± 35	–21.3	3.4	Human	SUERC-2028	1155 ± 35	–19.4	9.7
		SUERC-2670	1115 ± 35	–21.5	n/a					
		Weighted mean	1150 ± 25							
Grímsstaðir	Horse (*Equus* sp.)	SUERC-2019	1145 ± 35*	–21.0*	1.7*	Human	SUERC-2018	1225 ± 35*	–19.3*	10.0*
		SUERC-2662	1105 ± 35*	–20.7*	1.2*					
		Weighted mean	1125 ± 25							
Gautlönd	Dog (*Canis* sp.)	SUERC-2664	1175 ± 35*	–20.5*	8.3*	Human	SUERC-2026	1200 ± 35*	–19.5*	8.4*
		SUERC-2352	1170 ± 40*	–20.5*	n/a		SUERC-2663	1175 ± 35*	–19.7*	7.7*
		Weighted mean	1173 ± 26				Weighted mean	1188 ± 25		
Ytri-Neslönd	Horse (*Equus* sp.)	SUERC-2017	1175 ± 35*	–21.8*	2.7*	Human	SUERC-2016	1395 ± 35*	–18.9*	9.7*
		SUERC-2661	1200 ± 35*	–21.7*	2.0*		SUERC-2660	1405 ± 35*	–19.3*	8.3*
		Weighted mean	1188 ± 25				Weighted mean	1400 ± 25		

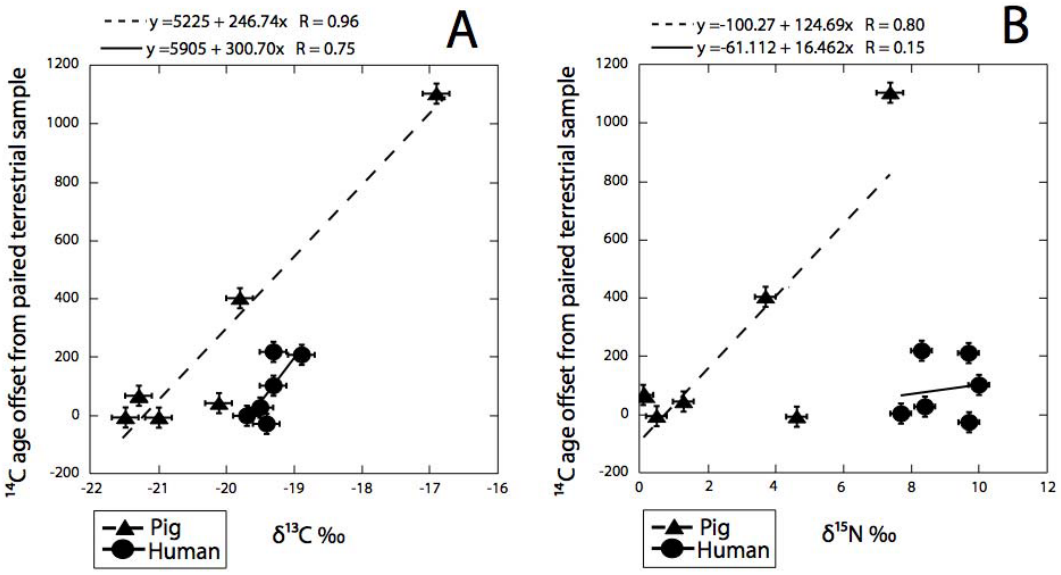

Figure 3 Plot of A: $\delta^{13}C$, and B: $\delta^{15}N$, versus ^{14}C age offset from terrestrial samples for archaeological samples of pig and human bone from Norse middens. The pig samples include previous measurement of a pig from Ascough et al. (2007).

The $\delta^{13}C$ values of horse bones from graves at Grímsstaðir, Glaumbær, and Ytri-Neslönd are in the range –20.7 to –21.8‰, indicating a diet of purely C_3 terrestrial vegetation. The $\delta^{13}C$ of the bone from the Gautlönd dog is –20.5‰, indicating that this animal did not consume significant quantities of non-terrestrial carbon. However, the $\delta^{15}N$ of this sample is significantly higher (+8.3‰) than any other domestic mammal bone, demonstrating a higher trophic level, as would be expected of this species. No consistent differences exist between the isotopic signatures in archaeological samples of horse, cow, and pig bone, with the exception of the slightly higher than average $\delta^{13}C$ value in the pig bone sample SUERC-3438. In contrast, there is a clear offset between the isotopic values of domestic mammal and human bone, where both $\delta^{13}C$ and $\delta^{15}N$ are consistently higher in human samples. However, in human bone there is no clear correlation between apparent ^{14}C age offset and $\delta^{15}N$, although there is some evidence for a relationship between ^{14}C age offset and $\delta^{13}C$ (Figure 3A and B).

The samples of Arctic char and brown trout from deposits at Hofstaðir have ^{14}C ages of 4930 ± 35 (SUERC-11539) and 4675 ± 35 (SUERC-11540) ^{14}C yr BP, respectively (Table 1). The apparent ^{14}C age of these samples suggests an FRE of at least ~3500 ^{14}C yr. This is much larger than those based on previous published values for Arctic char (Ascough et al. 2007), indicating FRE variation of >1500 ^{14}C yr during the Viking period. Values of $\delta^{15}N$ in the fish bone (+5.7 to +6.8‰) are close to the range of +5.6‰ to 6.0‰ for previously published data for Arctic char (Ascough et al. 2007). However, the $\delta^{13}C$ values for SUERC-11539 and -11540 are –12.2‰ and –12.5‰, respectively, and significantly heavier than previously published values (Ascough et al. 2007).

Modern Samples

Six samples of modern biota from around Lake Mývatn show ^{14}C activities (Table 2) that are commensurate with those estimated for atmospheric carbon in 2008 (105.50 pMC by extrapolation from the curve of Hua and Barbetti [2004]). The percent modern carbon (pMC) of this material ranges from 102.37 ± 0.45 to 151.15 ± 0.66 pMC. The majority of these values are consistent with current atmospheric ^{14}C concentrations for the Northern Hemisphere; however, it should be noted that the

cow bone value of 151.15 ± 0.66 pMC (SUERC-19790) means this animal is likely to have died ~30 yr before this sample was measured (Levin and Kromer 1997, 2004; Levin et al. 2007). With the exception of SUERC-19802 (grebe feather), $\delta^{13}C$ values of these samples (−26.3‰ to −21.4‰) are characteristic of a C_3 plant dominated terrestrial environment, with values of −28.3‰ to −29.1‰ in grass samples close to the lake shore. Likewise, the $\delta^{15}N$ of these samples (+1.3‰ to +6.5‰) are within the range of the bone collagen from archaeological terrestrial mammals. In SUERC-19802 (grebe feather), a $\delta^{13}C$ of −14.6‰ and $\delta^{15}N$ of +8.6‰ indicates a non-terrestrial dietary component, possibly including aquatic carbon from Lake Mývatn. However, the pMC of this sample is consistent with levels for the modern period.

Table 2 Results of ^{14}C and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) measurements on modern samples of biota and detritus from Mývatn.

Sample type	Sample ID	pMC (±1 σ)	^{14}C age BP (±1 σ)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Arctic char (*Salvelinus alpinus*)	SUERC-19788	52.05 ± 0.23	5245 ± 35	−14.0	+5.8
Stickleback (*Gasterosteus aculeatus*)	SUERC-19789	64.21 ± 0.28	3560 ± 35	−13.4	+5.4
Chironomid adult midge (*Tanytarsus gracilentus*)	SUERC-19791	57.13 ± 0.25	4495 ± 35	−14.4	+0.5
Chironomid larvae (*Tanytarsus gracilentus*)	SUERC-19792	58.81 ± 0.26	4265 ± 35	−11.8	−1.7
Bulk zooplankton	SUERC-19793	57.51 ± 0.25	4445 ± 35	−17.7	+1.5
Lake benthic detritus	SUERC-19797	57.72 ± 0.25	4415 ± 35	−16.4	−0.5
Alternate water milfoil (*Myriophyllum alterniflorum*)	SUERC-19800	62.04 ± 0.27	3835 ± 35	−10.2	−1.3
Claspingleaf pondweed (*Potamogeton perfoliatus*)	SUERC-19801	60.28 ± 0.26	4065 ± 35	−12.5	+0.8
Cow (*Bos sp.*)	SUERC-19790	151.15 ± 0.66	—	−21.4	+6.2
Grass (*Poa sp.*): Haganes	SUERC-19798	105.38 ± 0.46	—	−28.3	+1.3
Grass (*Poa sp.*): Kalfastrond	SUERC-19799	105.66 ± 0.46	—	−29.1	+2.6
Grass (*Poa sp.*): Seljahjallagil	—	—	—	−28.5	−9.1
Field horsetail (*Equisetum arvense*): Seljahjallagil	—	—	—	−26.9	−2.6
Horned grebe (*Podiceps auritus*)	SUERC-19802	102.37 ± 0.45	—	−14.6	+8.6
Mallard (*Anas platyrhynchos*)	SUERC-19803	103.10 ± 0.45	—	−26.3	+6.5
Common snipe (*Gallinago gallinago*)	SUERC-19807	109.85 ± 0.48	—	—	—

Eight samples of modern material obtained from within Lake Mývatn have pMC values of between 52.05 ± 0.23 and 64.21 ± 0.28 pMC. This gives a ^{14}C age range of 3560 ± 35 to 5245 ± 35 ^{14}C yr BP, indicating that samples at all major trophic levels within the lake are affected by a FRE of at least ~3500 ^{14}C yr. These samples have heavier $\delta^{13}C$ values than those from the Mývatn terrestrial ecosystem, with values of −10.2‰ to −17.7‰. $\delta^{15}N$ values appear closely related to trophic position, with the highest values (+5.4‰ to +5.8‰) in the 2 fish samples (SUERC-19788 and -19789). Notably, $\delta^{15}N$ values for primary producers and consumers within the lake are between −1.7‰ and +0.8‰, i.e. lower than values for terrestrial samples.

The pMC of water samples ranged between 26.71 ± 0.12 and 55.23 ± 0.21 pMC, giving a ^{14}C age range of 10,605 ± 35 to 4770 ± 30 ^{14}C yr (Table 3). Both water ^{14}C activity and $\delta^{13}C$ are correlated with sample source. Warm, geothermally influenced water at Helgavogur has a low ^{14}C activity and a heavy $\delta^{13}C$ signature, whereas the reverse is true of water at distance from the groundwater springs in the lake surface mixing zone (Station 33).

Table 3 Results of ^{14}C and $\delta^{13}C$ analysis of water samples from 3 locations in Lake Mývatn.

Site	Description	Sample ID	$\delta^{13}C$ (‰)	pMC (±1 σ)	^{14}C age BP (±1 σ)
Grjotavogur	Cold spring	SUERC-23580	−7.4	42.54 ± 0.16	6865 ± 30
Helgavogur	Hot spring	SUERC-23581	−5.2	26.71 ± 0.12	10,605 ± 35
Station 33, middle of South Basin	Mixed surface	SUERC-23582	−8.1	55.23 ± 0.21	4770 ± 30

DISCUSSION

The results demonstrate that ^{14}C ages of some pig and human bone collagen samples from archaeological sites in Mývatnssveit are anomalously old due to a ^{14}C reservoir effect. Although marine resources are found on sites in this region (McGovern et al. 2006, 2007), the marine reservoir effect (MRE) for Icelandic coastal waters in the Viking period was ~500 ^{14}C yr (Eiríksson et al. 2000, 2004; Ascough et al. 2007). An offset of 100–400 ^{14}C yr in tissues of terrestrial organisms produced via the MRE would therefore require a diet that contained a large amount of marine resources. For example, seal bone from a north Icelandic Viking-period midden with a reservoir age of ~470 ^{14}C yr had a $\delta^{13}C$ of −12.7‰ and $\delta^{15}N$ of 14.4‰, typical of a 100% marine diet (Ascough et al. 2007). The heaviest $\delta^{13}C$ and $\delta^{15}N$ values for pig and human bone presented here are −18.9‰ and +10.0‰, respectively. These $\delta^{13}C$ values do not provide evidence for a diet that is high in marine resources. Therefore, given a FRE of up to ~3500 ^{14}C yr, the most likely explanation for the ^{14}C age offsets of up to ~400 ^{14}C yr in this sample group is the incorporation of a small percentage of freshwater dietary carbon. This is supported by the fact that although marine mammal and fish remains are recovered from Viking middens in the region, the majority of archaeofauna recovered at archaeological sites stem from terrestrial and freshwater fauna (e.g. McGovern et al. 2006, 2007).

Even within the relatively small sample group represented here (5 pigs, 6 humans), the ^{14}C age offset from terrestrial samples varies considerably (i.e. from 0 to 400 ^{14}C yr). This is likely to result from variations in the content of aquatic protein in the diet. However, the ability to both precisely quantify the proportion of aquatic resources consumed by an individual and to accurately correct for the Mývatn FRE in affected samples is limited. This is because of 1) lack of a clear correlation between stable isotope values and ^{14}C age offsets, 2) clear evidence for temporal fluctuations in the size of the Mývatn FRE, and 3) the likelihood of significant spatial variation in the Mývatn FRE.

Measurements of $\delta^{15}N$ produced values of +1.0‰ to +5.9‰ in terrestrial herbivore bones from Mývatnssveit with a variation of up to 4.9‰ between different individuals of the same species. This presumably reflects a wide range in $\delta^{15}N$ values of dietary resources consumed by different individual animals, meaning at least some of the sampled animals were feeding upon plants with $\delta^{15}N$ <+1‰. This is supported by the depleted values of $\delta^{15}N$ in grass and field horsetail from Seljahjallagil, which gave values of −9.1‰ and −2.6‰, respectively. Also, research by Wang and Wooller (2006) demonstrated dominantly negative $\delta^{15}N$ values in terrestrial vegetation around 4 Icelandic lakes, with values as low as −12.4‰ in some lichens. Plant $\delta^{15}N$ is likely to reflect factors of N sources (i.e. NH_4^+, NO_3^- and amino acids), water availability and processes of soil N mineralization and immobilization at specific sites (Evans 2001) and lower $\delta^{15}N$ values are known to be a feature of many temperate environments (Martinelli et al. 1999; Welker et al. 2003). In contrast, the higher $\delta^{15}N$ values measured in terrestrial herbivore bone collagen appear to reflect the $\delta^{15}N$ values of some modern terrestrial plants in proximity to the lake, which are in the range +1.3‰ to +2.6‰. Investigation of plant $\delta^{15}N$ around Mývatn did not suggest enrichment due to midge infall into terrestrial habitats (Gratton et al. 2008); however, plant $\delta^{15}N$ may be increased as a result of artificial fertiliza-

tion (e.g. Meints et al. 1975; Sah 2005). Fertilization may also have formed a significant part of Norse agricultural practices in Mývatnssveit (McGovern et al. 2007; Adderley et al. 2008). Importantly, the range of $\delta^{15}N$ values in archaeological and modern terrestrial herbivores (+1.0‰ to +6.2‰) shows considerable overlap with the $\delta^{15}N$ values of both modern and archaeological freshwater fish from Mývatn (i.e. +5.4 to +6.8‰). Therefore, although the $\delta^{15}N$ of about +9.0‰ observed in the group of human samples could result from consumption of freshwater resources, these values could equally reflect consumption of meat from terrestrial herbivores. This may explain the lack of correlation between $\delta^{15}N$ and herbivore-omnivore ^{14}C offset observed in the pig and human samples.

In contrast, the $\delta^{13}C$ values of terrestrial versus freshwater material in Mývatnssveit are distinct. Values for both archaeological and modern fish (−12.2‰ to −14.0‰) are significantly heavier than those of terrestrial herbivores (i.e. −20.3‰ to −21.8‰). Therefore, the $\delta^{13}C$ values for terrestrial omnivores should increase with aquatic dietary component and be positively correlated with ^{14}C age offset. This is true in the pig previously analyzed from Mývatn by Ascough et al. (2007), where $\delta^{13}C = -16.9‰$ and $\delta^{15}N = +7.4‰$ and these were accompanied by a ^{14}C age offset of 1100 ^{14}C yr. In the archaeological samples presented here, the relationship between $\delta^{13}C$ and ^{14}C age offset is less clear. Although the pig bone affected by the FRE (SUERC-3438) has a slightly heavier $\delta^{13}C$ signature than unaffected samples, the $\delta^{13}C$ of the human bone with a significant ^{14}C age offset is not significantly different from unaffected samples. This is a likely result from the size of the Mývatn FRE, which, on the basis of our data, appears to be between 1500–3500 ^{14}C yr for the period studied. A reservoir effect of this size means that even a relatively small quantity of freshwater protein in the diet would result in a significant reservoir age in omnivore bone collagen but would not result in a significant shift in sample $\delta^{13}C$. For example, even taking the smallest offset presently calculated for the Mývatn FRE of 1505 ^{14}C yr (Ascough et al. 2007) as characteristic of a 100% freshwater diet (where a 0 ^{14}C yr offset arises from 100% terrestrial diet), a shift of ~200 ^{14}C yr, as observed in human bone from Ytri-Neslönd, could result from little more than 10% aquatic carbon. Obviously, with a larger FRE, such a shift in ^{14}C age could be achieved with input of even less dietary freshwater carbon. However, a 10% inclusion of freshwater aquatic carbon may not result in a large shift in bone collagen $\delta^{13}C$ from values typical of organisms consuming terrestrial resources. For example, if cattle bone $\delta^{13}C$ is taken to represent a 100% terrestrial resource, and freshwater fish $\delta^{13}C$ to represent a 100% aquatic resource, using the values presented in this paper and in Ascough et al. (2007), a 10% inclusion of aquatic carbon would result in a $\delta^{13}C$ of –20.5‰ (Figure 4). Even allowing for a ~1‰ positive shift in $\delta^{13}C$ due to trophic level, this data suggests that with such a large FRE, identification of samples that contain FRE-affected carbon via stable isotopes could only be achieved if the proportion of aquatic carbon consumed represented a relatively large proportion of the total diet.

Analysis of both archaeological and modern samples reveals that the Mývatn FRE varies considerably with time and that modern FRE values are higher than during the Viking period, reaching a maximum offset of ~5200 ^{14}C yr. Archaeological fish bone measurements (SUERC-11539 and -11540) suggest that FRE fluctuations of ~2000 ^{14}C yr during a period of ~100 calendar yr occurred during the Viking period. This may be due to variation in the amount of geothermal activity in active zones near the lake, as ^{14}C measurements in water samples mechanistically link the FRE to inputs of geothermally influenced groundwater. Alternatively, this may reflect a spatial variation in FRE within the lake. If so, variation in FRE ^{14}C offsets between fish may reflect differences in harvesting of freshwater resources, where organisms with a larger FRE were sourced in closer proximity to inflow regions of geothermally influenced groundwater. The ^{14}C activity in such groundwater generally decreases with increasing temperature, as increasing quantities of CO_2 are derived via dissolution of ^{14}C-dead carbon from basaltic rocks in a series of geothermal water-rock interactions

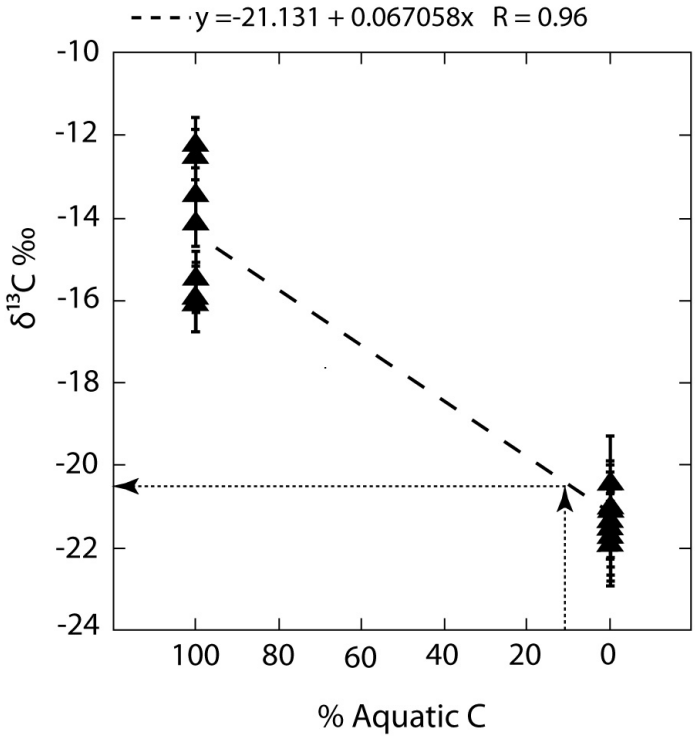

Figure 4 Linear mixing line of cattle bone $\delta^{13}C$ (100% terrestrial resource) versus freshwater fish $\delta^{13}C$ (100% aquatic resource) using the values presented in this paper and in Ascough et al. (2007).

(Sveinbjörnsdóttir et al. 1995). Consequently, the lowest ^{14}C activity in water from Mývatn is observed in the warm groundwater springs at Helgavogur. Geothermal influence is derived from the Námafjall geothermal field, which is located within a fissure swarm across the Krafla geothermal center (Kristmannsdóttir and Ármannsson 2004). Therefore, temporal variation in geothermal activity in this area, as has been observed for several periods during the Holocene (e.g. Björnsson et al. 1979; Thórarinsson 1979; Sæmundsson 1991), would be likely to affect the ^{14}C activity of inflowing groundwaters, resulting in temporal fluctuations in FRE.

In modern lake samples, stable isotope analyses were undertaken in conjunction with ^{14}C measurements to investigate any covariance between these variables. Such variation may reveal whether differences between FRE values in aquatic biota could be linked to factors of ecosystem position or trophic level. However, no clear relationship exists between stable isotope and ^{14}C values in FRE-influenced aquatic samples. This suggests that along with temporal variation, there may be a spatial variation in FRE within the lake at any point in time and that trophic transfer of the FRE is complex. Understanding such variation requires further investigation of a larger and more systematic set of samples to enable a spatial analysis of the FRE within Lake Mývatn, together with a more comprehensive isotopic study of freshwater vegetation and biota. Such a study would provide not only useful information on FRE variation over a single time interval for archaeological sample chronologies but would also allow an investigation of the transfer of ^{14}C within aquatic ecosystems, particularly in regions with active volcanism and large drainage catchments in Arctic environments.

CONCLUSIONS

Analysis of modern and archaeological samples from Mývatnssveit demonstrates the presence of a large ^{14}C FRE within Lake Mývatn, as a result of geothermally influenced groundwater inputs with low ^{14}C activity. This FRE varies from ~1500 to over 5000 ^{14}C yr between the period AD 868–1148 and present. Additional evidence suggests significant variation in FRE within Lake Mývatn due to factors of spatial location and ecosystem dynamics, although this is not yet well constrained. The Mývatn FRE is transferred to terrestrial organisms consuming freshwater resources, including pigs and humans. Therefore, the FRE has important implications for archaeological chronologies in the region and Iceland in general, as ^{14}C ages of some omnivorous organisms may be erroneously old. The large variability in the FRE is likely to result from activity changes in geothermal fields from which groundwater influx is sourced to the lake. These variations mean that the use of a single value is not applicable to correct samples from Mývatnssveit for the FRE, rendering accurate correction of such ^{14}C ages effectively impossible in the absence of paired samples of terrestrial material of demonstrably equivalent age. We would therefore recommend that archaeological chronological information in this region be preferentially obtained using ^{14}C measurements of terrestrial herbivore bones and plant macrofossils, rather than organisms likely to have consumed freshwater dietary resources. It should be noted that although ^{14}C measurements of omnivores from north Iceland should clearly be treated with caution, many such samples within this study did not appear affected by the FRE. However, if the only available material for dating is that of omnivorous species, efforts should be made to ensure that sample ^{14}C ages are not influenced by the FRE. Even if a single FRE correction value could be used, the results demonstrate the danger in using bulk stable isotopes to correct for a known reservoir effect where 1) a mixed and complex diet is likely to have been consumed, 2) there is significant overlap in the signature of one or more isotopes between different systems, and 3) where the ^{14}C reservoir effect is sufficiently large that even a relatively small quantity of aquatic carbon in the diet will significantly alter the sample ^{14}C activity. These factors should be thoroughly considered before identification and correction for dietary reservoir effects is attempted, in order to assess the level of precision and accuracy to which such corrections can be made.

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